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DEVELOPMENT OF A LIGHT WEIGHT 25mm EXPLOSIVE PROJECTILE

AAI CORPORATION
INDUSTRY LANE
COCKEYSVILLE, MARYLAND 21030

JUNE 1977

FINAL REPORT FOR PERIOD MARCH 1976-JANUARY 1977

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Design and analysis of an improved 25mm high explosive incendiary (HEI) projectile is discussed. Improved performance is accomplished by configuration changes which reduce projectile weight, improve aerodynamic performance, and increase the high explosive material. The improvements are achieved by thinning the projectile walls, by the choice of material, heat treat, and incorporation of a plastic rotating band. The design and analytical work performed in developing this improved projectile are reviewed.

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SUMMARY

A program of analysis, design, and fabrication was conducted to seek out new concepts for an air-to-air projectile that will have superior performance in the air combat mission. The projectile is intended for use in a fully telescoped cartridge concept and, therefore, departs from conventionally configured ammunition where the projectile and case are tandomly arranged with the projectile forward of the case. This removes some of the constraints associated with conventional ammunition design and permits the consideration of new approaches and concepts.

One of the most important parameters in determining the effectiveness of air-to-air gun systems is the time of flight to the target. At the shorter ranges, given a particular propellant charge, and a projectile shape and caliber, this time of flight can be reduced significantly by a lighter weight projectile. An objective, therefore, of this program was to develop a minimum weight design which can be used as a baseline configuration for this projectile.

A 25mm projectile was investigated which was equipped with a modified M505 fuze and had an external configuration conforming in shape to the GAU-7/A, PJU-2/B HEI projectile. A variety of concepts were investigated. The distinguishing characteristics of each concept were the design of the plastic rotating band and the internal configuration. Minimum weight designs for each concept were developed using a finite element analytical technique. Performance parameters such as stability, time of flight, charge-to-mass ratio, flyoff velocity, and fragment distribution were computed for each design. Using this information, a review of each design was conducted, and engineering judgement used to select a design of which 36 models were fabricated for test.

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PREFACE

This program was conducted by the AAI Corporation, Industry Lane, Cockeysville, Maryland 21030, under Contract F08635-76-C-0192 with the Air Force Armament Laboratory, Armament Development and Test Center, Eglin Air Force Base, Florida. Captain Woodrow S. Gilliland (DLDG) managed the program for the Armament Laboratory. The program was conducted during the period from March 1976 to January 1977.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

GERALD P. D'ARCY, Colonel, USAF
Chief, Guns, Rockets and Explosives Division

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SECTION I

INTRODUCTION

The Air Force is sponsoring a program to seek out new concepts for an air-to-air projectile that will have superior performance in the air combat mission. Air-to-air combat effectiveness can be improved by increasing the probability of hitting the target and by greater warhead lethality. A short time of flight at ranges out tc 2500 feet is important in achieving a satisfactory hit probability. Given a projectile caliber and shape, the most effective means to reduce the time of flight at short ranges is to increase the muzzle velocity. This can be accomplished by minimizing the weight of the projectile; therefore, the objective of the program was, working within a set of physical constraints, to develop a design for the projectile that was as lightweight as possible consistent with the satisfaction of the necessary performance parameters.

This projectile will be used in a fully telescoped cartridge. This removes some of the constraints associated with the design of conventionally configured ammunition where the projectile and cartridge case are tandomly arranged. This freedom to pursue new concepts was exercised in the development of a plastic rotating band concept that restricts the propellant gases to the region behind the projectile. This shielding effect minimizes the loads on the projectile walls and helps in achieving minimum projectile weight.

The specified constraints were the caliber (25mm), the barrel length and rifling, the ogive shape, projectile length, fuze thread dimensions, and the variation with time of the chamber pressure. Performance parameters that influenced the design were the requirement for adequate projectile stability and the need for satisfactory shell fragmentation properties. The materials, the heat treat process, the internal projectile configuration and the design of the rotating band were unconstrained areas. This provided the freedom to achieve a lightweight projectile design that promises significant improvements in short range projectile performance. For example, compared to the GAU-7/A, PJU-2/B HEI projectile the weight has been reduced 21 percent, muzzle velocity increased 21 percent, time of flight to 2500 feet reduced 13 percent, the HE charge increased 30 percent, and the charge-to-mass ratio increased 140 percent. Other improvements are expected to be compatibility with the telescoped case design, good control of balloting in the case and gun tubes, and improved reliability of a plastic rotating band.

SECTION II

INVESTIGATIONS

1. ANALYTICAL APPROACHES AND DESIGN CONSTRAINTS

The Air Force Armament Laboratory, the sponsor of this program, directed that the external configuration of the 25mm projectile originally developed for the GAU-7A gun be used in designing this lightweight projectile. Other constraints were:

- The fuze thread dimensions were specified
- A modified M505 fuze should be employed
- The chamber and base pressure time and space history were specified
- The gun barrel rifling characteristics were provided.

No other constraints were applied, leaving open for study and analysis important parameters such as the internal projectile configuration, rotating band design, and choice of materials.

The external configuration of the projectile, designated the PJU-2/B HEI projectile shape, is shown in Figure 1. Except for the band seat and the crimp groove, this external configuration was used in all the projectile designs.

The variation of the chamber pressure used in the analytical computations is shown in Figure 2 and Table 1. Figure 2 shows this variation with projectile barrel travel, and Table 1 provides the variation with time. The characteristics of the rifling in the gun barrel is summarized in Table 2.

The objective of the program was that, working within the constraints listed above, a projectile design be developed that had minimum weight consistent with the requirements for adequate flight stability and acceptable terminal ballistic performance. The minimum weight criterion was important for it provides the shortest time of flight out to the combat ranges of interest. In order to achieve minimum weight designs, a finite element analytical technique was employed to compute structural properties. Details of this technique are presented in a subsequent section.

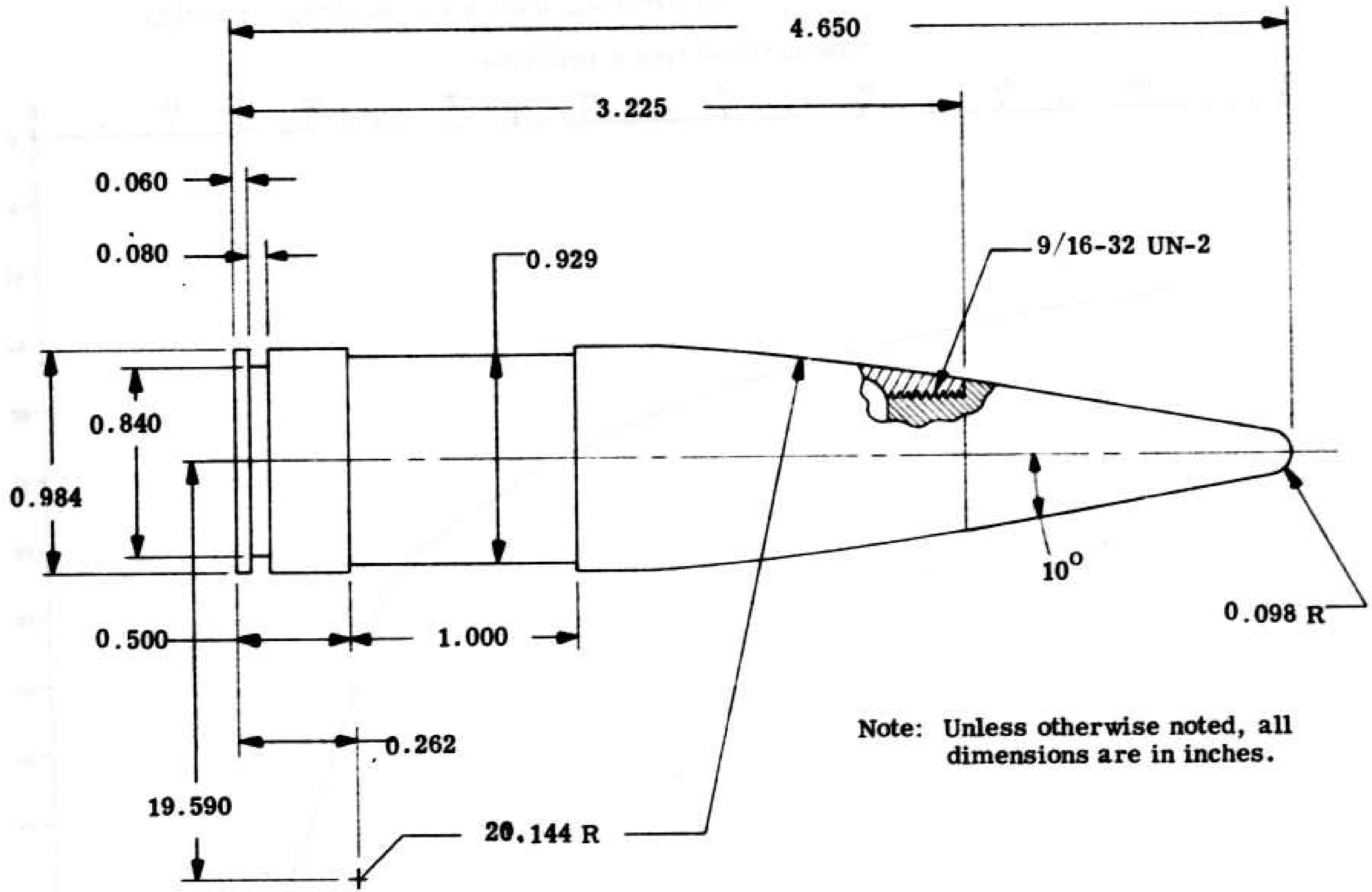


Figure 1. 25mm PJU-2/B Projectile - External Configuration

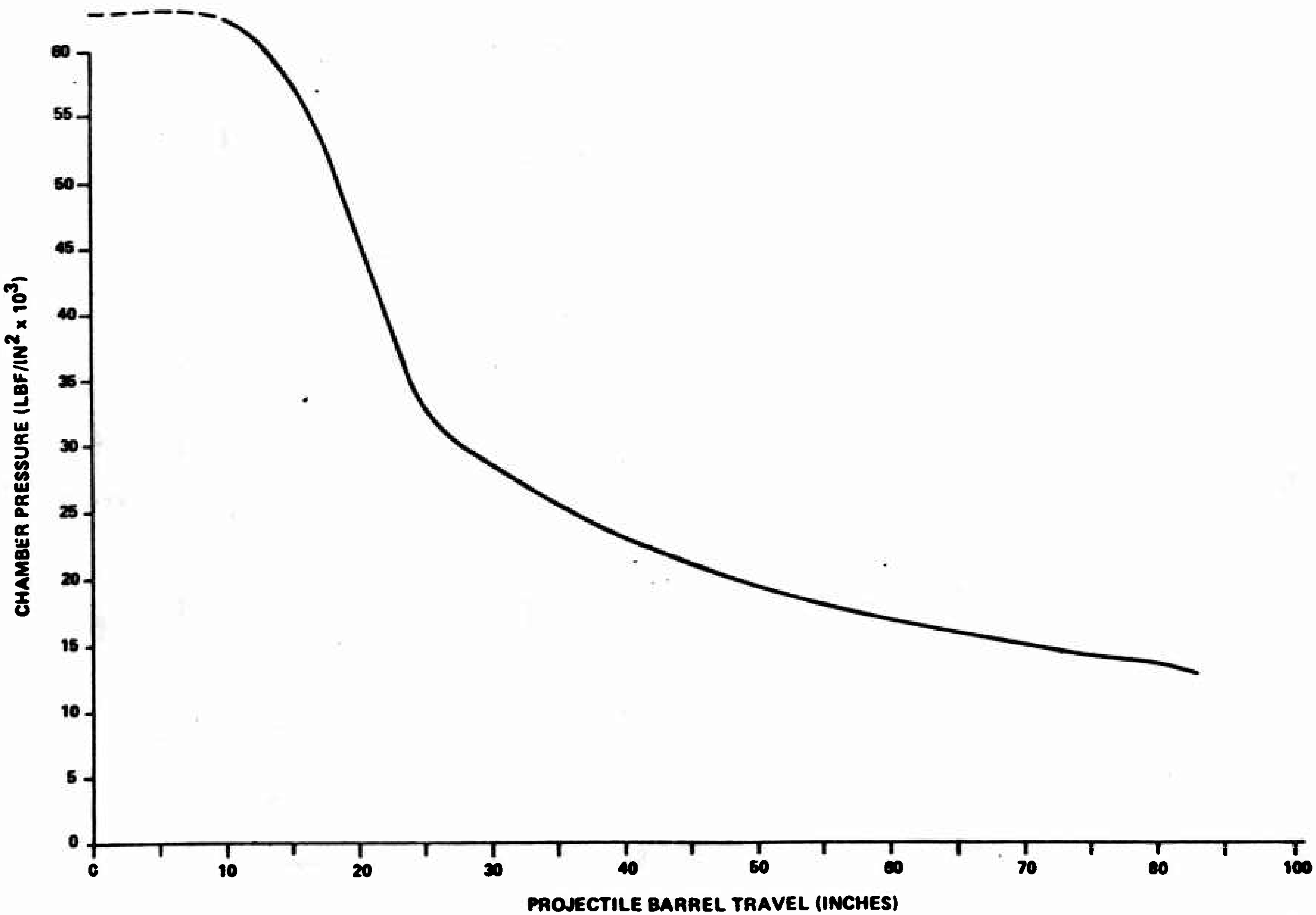


Figure 2. Variation of Chamber Pressure with Projectile Barrel Travel

TABLE 1. VARIATION OF CHAMBER AND BASE PRESSURE WITH TIME AND BARREL TRAVEL

Time (ms)	Chamber Pressure (psi)	Base Pressure (psi)	Travel (in.)
0.000	0	0	0.00
0.100	2400	2400	0.01
0.200	1624	1623	0.03
0.300	1671	1671	0.06
0.400	1718	1718	0.11
0.500	1765	1765	0.16
0.600	1812	1811	0.22
0.700	1859	1858	0.30
0.800	1906	1905	0.39
0.900	1953	1952	0.50
1.000	2000	1999	0.61
1.100	2100	2099	0.75
1.200	2200	2198	0.89
1.300	2300	2298	1.06
1.400	2400	2397	1.24
1.500	2500	2497	1.43
1.600	2920	2915	1.65
1.700	3340	3333	1.88
1.800	3760	3751	2.14
1.900	4180	4168	2.43
2.000	4600	4584	2.74
2.100	3550	3535	3.09
2.200	2500	2488	3.46
2.300	7250	7209	3.86
2.400	12000	11909	4.31
2.500	16300	16122	4.84
2.569	21782	21463	5.28
2.600	24200	23794	5.50
2.700	32100	31271	6.31
2.800	40000	38355	7.33
2.900	49000	45849	8.62
3.000	55500	50125	10.23
3.030	56850	50689	10.78
3.100	60000	51726	12.19
3.200	61000	49733	14.50
3.300	55237	42191	17.15
3.400	49513	35761	20.10
3.500	44556	30556	23.30
3.600	40296	26353	26.71
3.700	36641	22946	30.29
3.800	33497	22165	34.04
3.900	30782	17874	37.91
4.000	28426	15971	41.91
4.100	26369	14375	
4.200	24563	13025	
4.300	22969	11873	
4.400	21554	10883	(1)
4.500	20292	10025	
4.600	19159	9277	
4.700	18139	8620	
4.800	17217	8040	
4.900	16379	7525	
5.000	15614	7066	
5.067	15187	6814	89.30

(1) Information in this range not available.

TABLE 2. GUN BARREL RIFLING CHARACTERISTICS

Station Inches	Rotation: Degrees Cumulative	Rotation: Degrees Difference Sta to Sta
0	0°	0°
2	0°	0°
2.938	0°	0°
3	0°	0° 42'
4	0° 42'	3° 13'
6	3° 55'	4° 58'
8	8° 53'	6° 23'
10	15° 16'	7° 37'
12	22° 53'	8° 45'
14	31° 38'	9° 49'
16	41° 27'	10° 48'
18	52° 15'	11° 44'
20	63° 59'	12° 38'
22	76° 37'	13° 29'
24	90° 6'	14° 19'
26	104° 25'	15° 6'
28	118° 31'	15° 53'
30	135° 24'	16° 38'
32	152° 2'	17° 22'
34	169° 24'	18° 5'
36	187° 29'	18° 46'
38	206° 15'	19° 27'
40	225° 42'	20° 8'

Station Inches	Rotation: Degrees Cumulative	Rotation: Degrees Difference Sta to Sta
42	245° 50'	20° 47'
44	266° 37'	21° 25'
46	288° 2'	22° 3'
48	310° 5'	22° 40'
50	332° 45'	23° 17'
52	356° 2'	23° 53'
54	379° 55'	24° 28'
56	404° 23'	25° 4'
58	429° 27'	25° 38'
60	455° 5'	26° 12'
62	481° 17'	26° 46'
64	508° 3'	27° 19'
66	535° 22'	27° 52'
68	563° 14'	28° 24'
70	591° 38'	28° 56'
72	620° 34'	29° 28'
74	650° 2'	29° 59'
76	680° 1'	30° 31'
78	710° 32'	31° 1'
80	741° 33'	31° 32'
82	773° 5'	7° 42'
82.5	780° 47'	24° 0'
84	804° 47'	

Interior ballistic performance calculations were performed using company computer programs developed for this purpose. The interior ballistic calculations were performed using the pressure travel information shown in Figure 2 and Table 1. It was assumed that a propellant will be developed that will have the faster burning properties needed to approximate this performance with this lightweight projectile.

Two exterior performance parameters were computed using company computer programs. One is trajectory information that gives downrange velocities and time of flight; the other is projectile stability. The combat range of primary interest is $\leq$2500 feet. The lightweight projectiles have a higher muzzle velocity and will traverse these short ranges in less time than the heavier versions. The lighter projectiles slow down faster than the heavier designs and, at some range beyond 2500 feet, a crossover will occur where the time of flight to the target will be less for the heavier projectile.

Three stability factors were computed, namely: gyroscopic stability, dynamic stability, and a relationship between these two factors. Gyroscopic stability (S_g) is the factor of primary interest in this projectile. Theoretically, for stable flight this factor should be equal to or greater than 1.0 ($\geq$1.0). However, a practical design value is considered to be 1.20 and designs were developed that satisfied this criterion. This consideration becomes the limiting factor in some of the designs and determines the configuration rather than structural properties when designing lightweight projectiles. Dynamic stability and the relationship between dynamic and gyroscopic stability were computed but were never determining factors in this program. Dynamic stability (S_d) should fall between zero and 2.0 ($0<S_d<2$). The relationship $S_g \geq 1/S_d(2-S_d)$ should also be satisfied. No problems were encountered in satisfying these criteria.

Terminal ballistic effects are monitored by three computed parameters. These parameters were the charge-to-mass ratio, the flyoff velocity, and the size distribution of the metal fragments. These parameters were computed for each design. The charge-to-mass ratio and the flyoff velocity are considered very good for these lightweight projectiles and, therefore, no attempt was made to improve these factors. Fragment size distribution is a parameter of concern because there is a tendency to produce more small fragments than desired. Distributions were computed by relationships developed by MOTT. This parameter will be investigated experimentally by the Air Force to determine actual distributions. More

favorable fragment distributions are obtained by increasing the wall thickness of the steel body which is at cross purpose with lightweight projectile goals. This is a trade-off situation that may require attention in any subsequent development work.

2. CONFIGURATION STUDIES

Four basic projectile configurations were generated during the study period and subjected to detail design and analysis. Each configuration passed through a number of design iterations before computations indicated that structural and performance criteria had been satisfied. The final configurations of each of these four concepts were designated Configurations 1A, 2B, 3C and 4I. Sketches showing important features of each design are presented in Figures 3, 4, 5 and 6, respectively.

Configuration 1A was derived from the GAU-7A design and shape except the crimp groove at the aft end of the projectile has been removed. The internal configuration, however, is completely revised and represents a minimum weight design for this concept. This approach was used as one of the concepts because it represents a conventional approach and mimics an established design in external characteristics.

Configuration 2B is similar to 1A with the rotating band moved aft. This configuration was studied because it has compatibility with the case design and confines the gas pressure to the aft end of the projectile.

Configuration 3C was investigated because it is innovative and represents a departure from conventional rotating band design. This type of band is sometimes called an obturator rather than a rotating band, but it serves the same purpose. This approach has been used on larger caliber projectiles and is similar to an obturator used on some sabot-launched projectiles. It has an added attraction in this application in that the external configuration presents a cylindrical surface of appreciable length that will support the projectile in the smooth barrel portion of the case. The band in this concept discards at the gun muzzle which creates some debris. This is an unfavorable situation and a principle reason for eliminating it as a choice for fabrication.

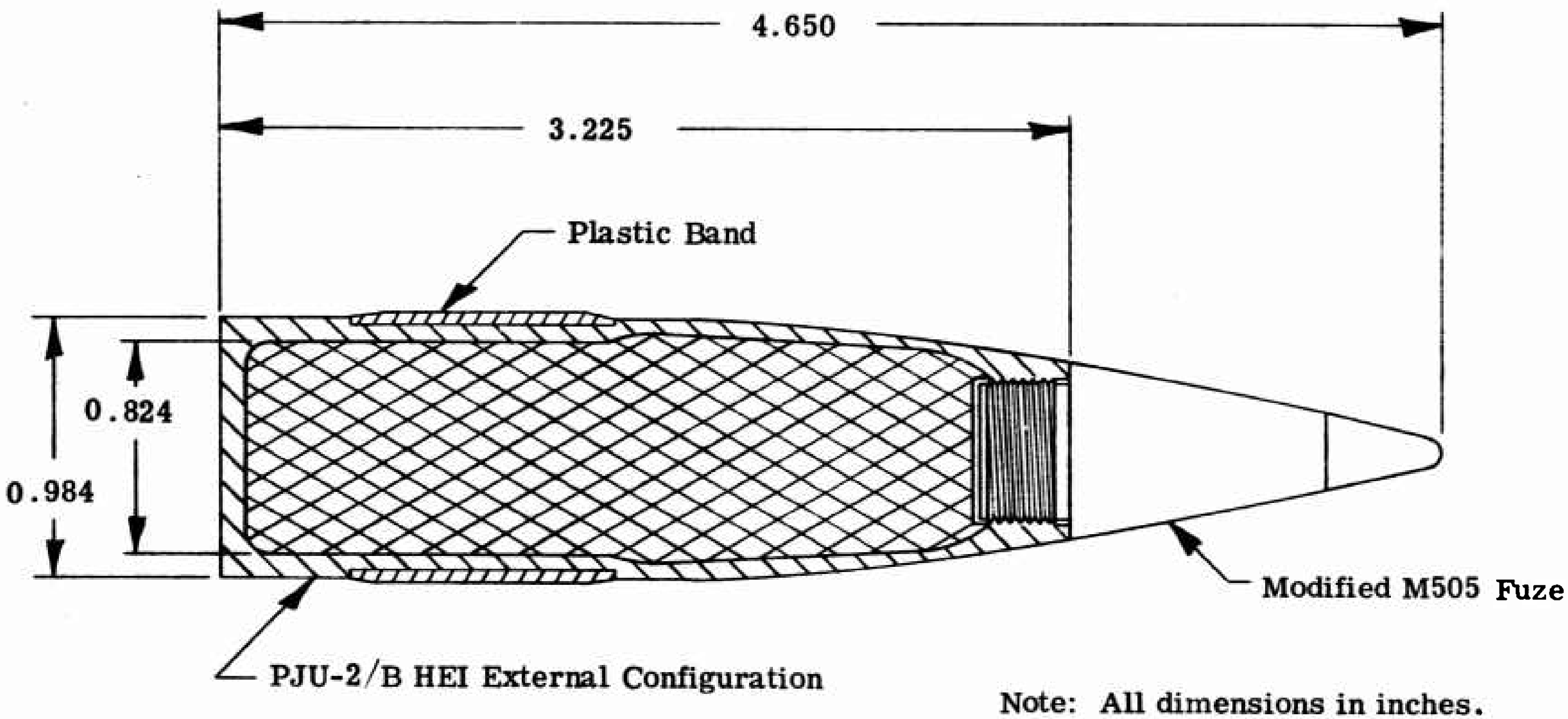
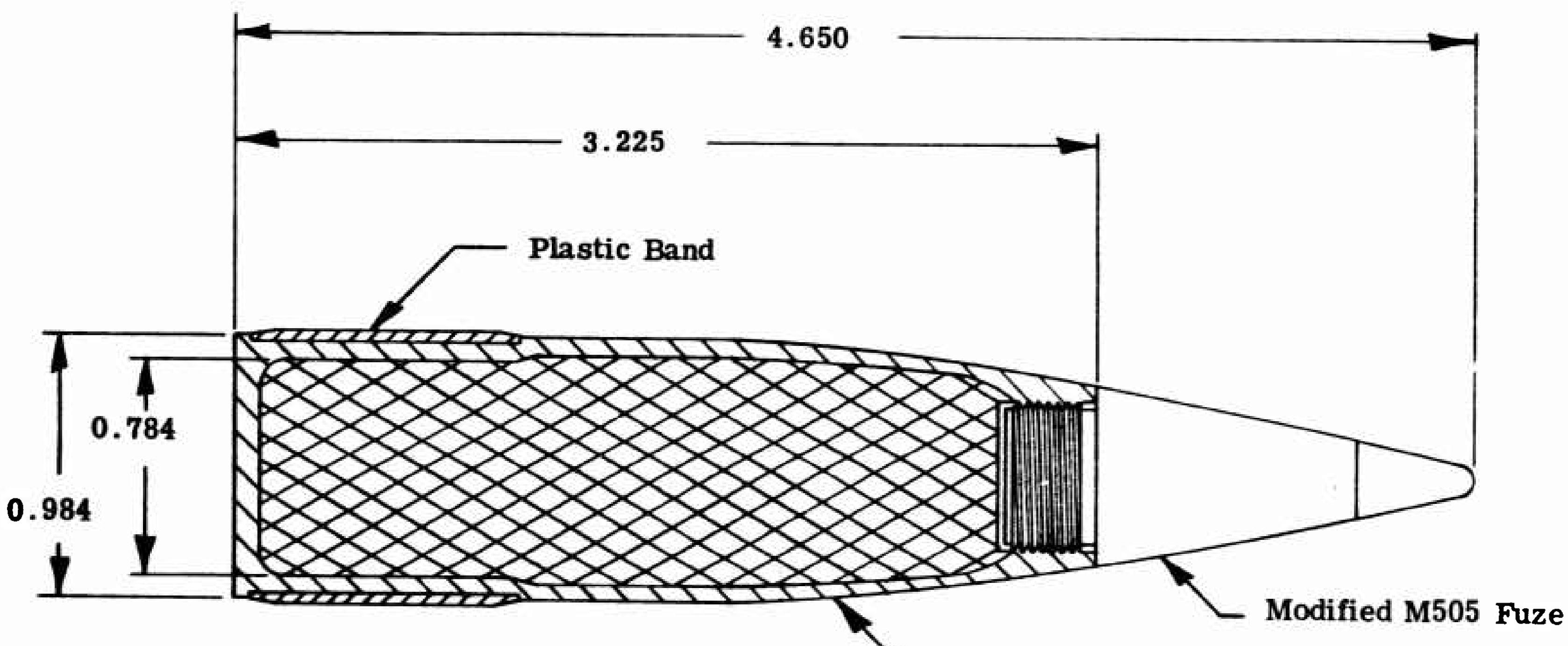


Figure 3. Projectile Configuration 1A



Note: All dimensions in inches.

Figure 4. Projectile Configuration 2B

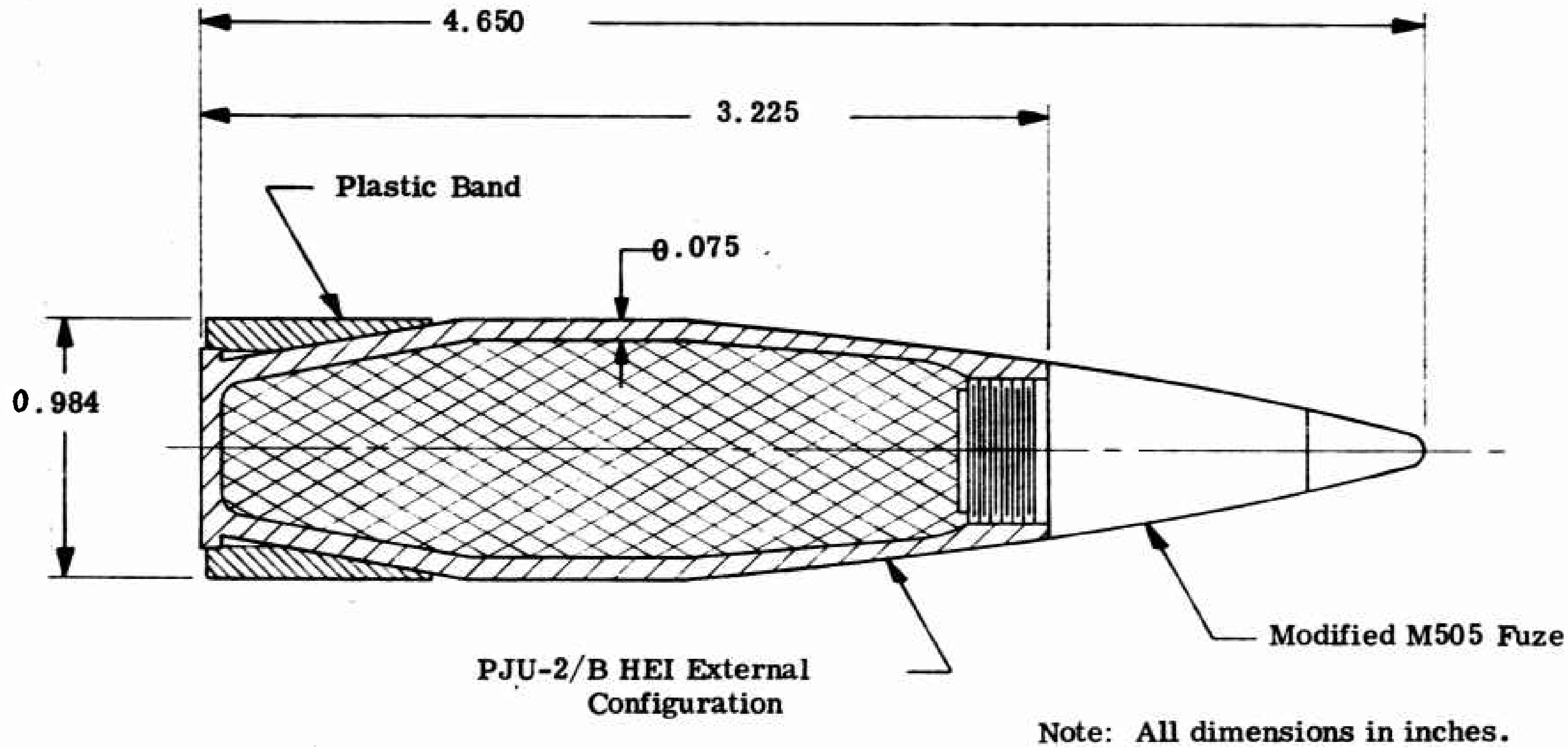
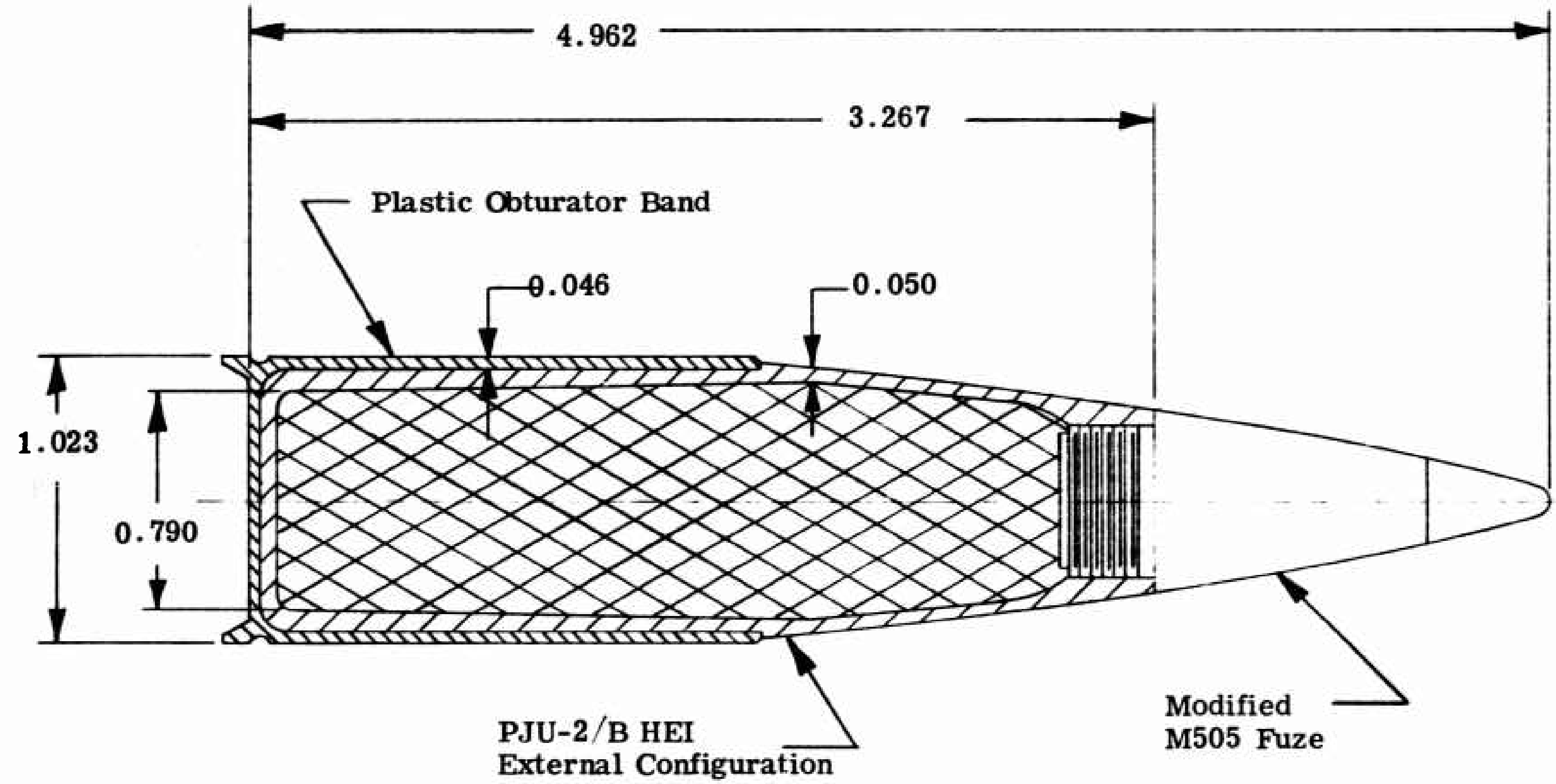


Figure 5. Projectile Configuration 3C



Note: All dimensions in inches.

Figure 6. Projectile Configuration 4I

Configuration 4I is the concept that was chosen for fabrication and test. It is innovative in concept in that the band encases the entire aft end of the projectile. It was rationalized that this should prevent propellant gases from entering the interface between the band and the projectile body and eliminate this as a cause of band failure. Also, the large interface surface between the band and the projectile body is believed to be favorable in maintaining the bond between these two parts. This design also has a lip at the aft end that serves as an obturator to prevent the escape of propellant gases during projectile travel in the smooth bore barrel section of the cartridge case. A further advantage is that the propellant gas pressure is confined to the aft portion of the projectile body which is conducive to good lightweight projectile design. A crimp groove is provided near the aft end that is engaged by the cartridge case barrel to retain the projectile in the case during handling and provide start pressure.

Details of the projectile body design are shown in Figures 7 and 8. Wall thicknesses of the projectile in the area covered by the rotating band were predicated upon the results of the structural analyses and represent a minimum weight design for the anticipated loading (see paragraph 3). Forward of the rotating band the computed stress levels are well below the allowable, but stability, manufacturing, and fragment distribution considerations indicate that it would be inadvisable to reduce the wall thicknesses beyond those represented by this design.

The rotating band design, except for its length and the wrap-around configuration at the aft end, is patterned after the designs employed on the GAU-7/A, PJU-2/B HEI projectile. The material is 612 nylon (ZYTEL® 158) polymer. The adhesive system consists of a polyamide-epoxy film using a primer underneath. The nylon 612 plastic is injection molded over this system and cured in place with the use of a cure sleeve and pressure plate to maintain pressure at the plastic-metal interface during a cure period at an elevated temperature.

Computed physical and performance characteristics of these four concepts are summarized in Table 3.

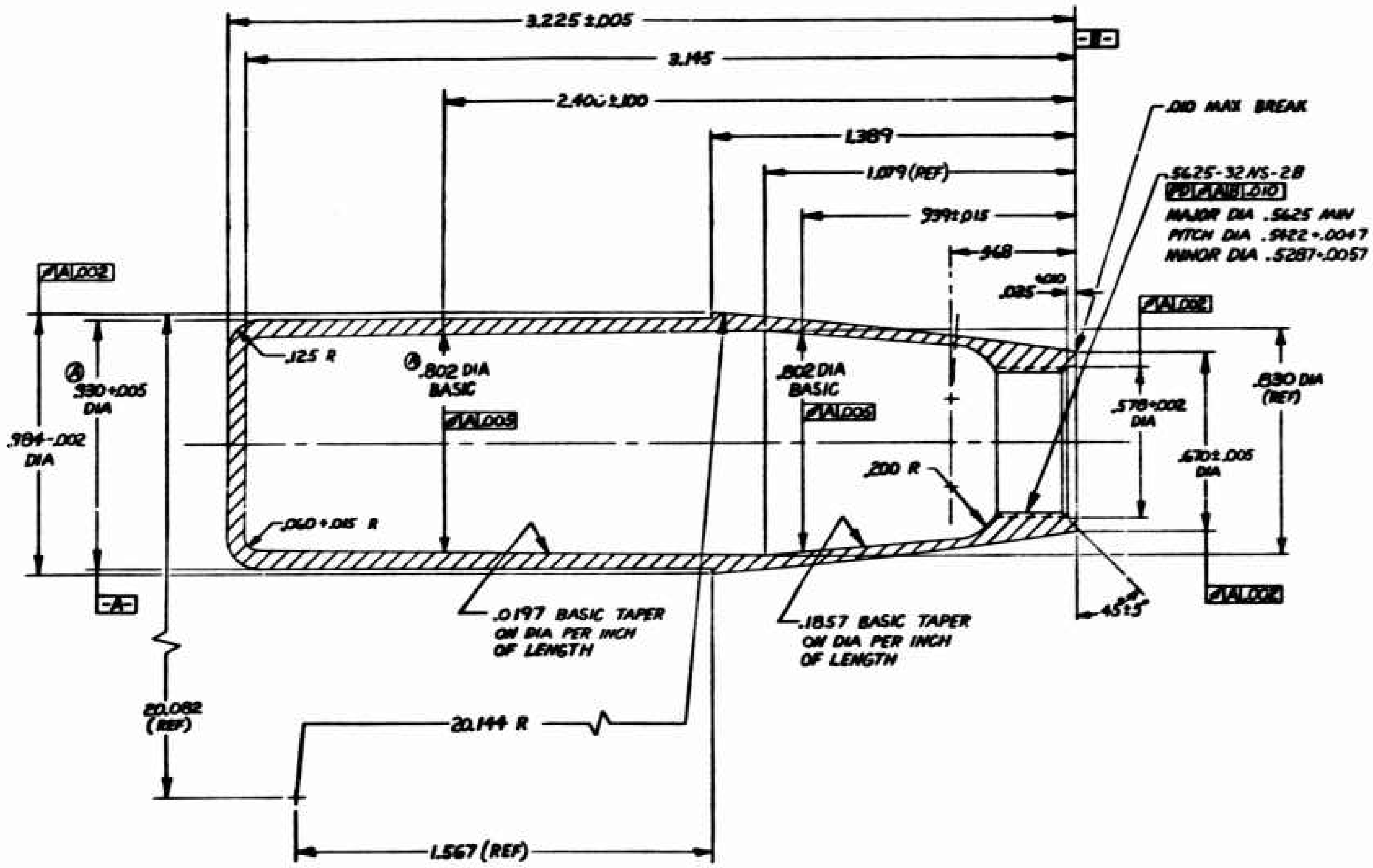


Figure 7. Projectile Body Design - Configuration 4I

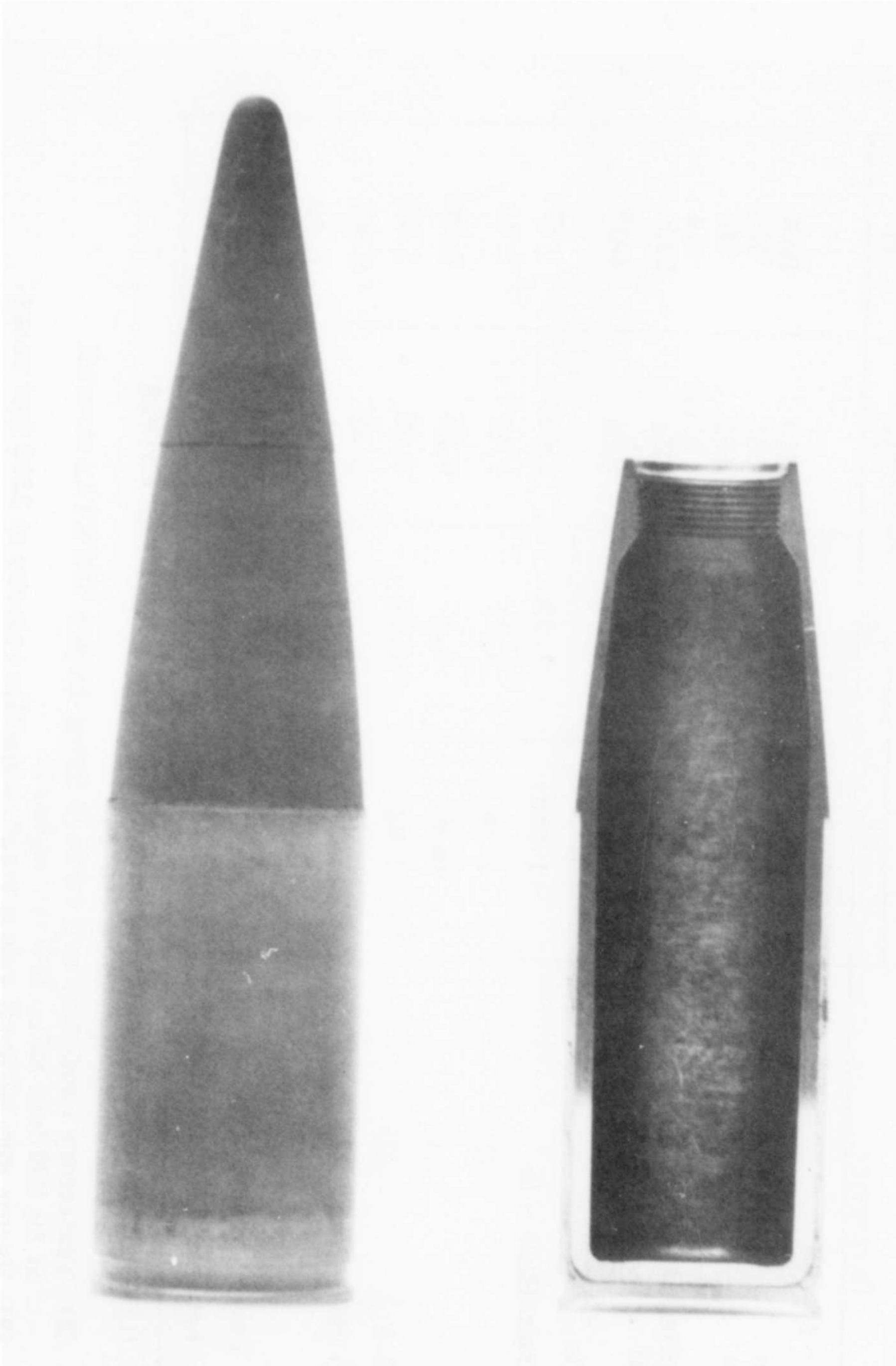


Figure 8. Views of Fabricated Projectile - Configuration 4I

TABLE 3. SUMMARY OF PHYSICAL AND PERFORMANCE CHARACTERISTICS OF FOUR PROJECTILE CONCEPTS

Parameter	Configuration			
	1A	2B	3C	4I
Weight - grains				
Case	1125	1156	1290	1082
Fuze	508	508	508	508
HE	661	654	553	626
Rotating Band	44	44	70 (4)	114
Total	2338	2361	2351	2330
V_{muzzle} - ft/sec	5197	4756	4663	4827
CG from Base - In.	1.850	1.830	1.960	1.854
S_g (1)	1.28	1.21	1.17	1.20
S_d (1)	0.86	0.87	0.85	0.866
$1/S_d\,(2-S_d)$ (1)	1.02	1.02	1.02	1.02
TOF to 2500 ft/sec (2)	0.45	0.48	0.43	0.45
C/M	0.59	0.57	0.43	0.60
Flyoff Vel - ft/sec (3)	7783	7477	6983	7598
Frags between 5 & 15 grains - %			24	19

Notes: (1) Stability conditions are forward firing from a 715 KTAS aircraft at sea level, temperature -40°F.

(2) Trajectory conditions are forward firing from a 550 KTAS aircraft at 10,000 feet MSL, ISO atmosphere.

(3) Vector sum of flyoff velocity and projectile velocity at 2500 feet range.

(4) Not included in total weight because it is discarded.

3. STRUCTURAL ANALYSIS AND DESIGN

The objective of the program was to develop a projectile design that is as lightweight as practical, working within a set of given constraints and consistent with the requirements for flight stability and satisfactory terminal performance. To achieve this minimum weight objective, a finite element analytical technique was employed to compute the stress levels throughout the projectile. This is a powerful method, for it allows the designer to alter the projectile configuration to achieve a uniform stress level throughout the projectile under varied conditions of loading.

The concept of finite element theory involves the dividing of a complex geometric structure into a finite number of substructures, each of which can readily be defined by geometry, material, and equilibrium equations. These substructures or elements are connected to each other at points called nodes or grid points. The collection of equations of equilibrium for all the elements are solved simultaneously to give grid point displacements. The displacements are used to calculate element forces and stresses. A computer is used to obtain a solution to the system of equations.

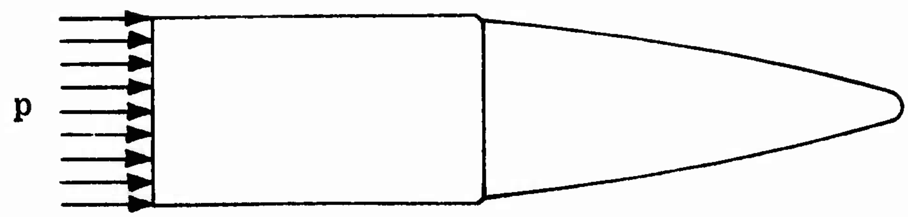
The program used to compute the stresses in the projectile was the NASTRAN system. NASTRAN is the acronym for Nasa Structural Analysis and was developed by NASA as a general purpose digital computer program for the analysis of complex structures. The NASTRAN program is currently capable of handling the following: static response to concentrated and distributed loads, thermal expansion, and enforced deformation; dynamic response to transient loads, steady-state sinusoidal loads, and random excitation; real and complex eigen values; dynamic and elastic stability analyses; and heat transfer analyses.

The first step in performing the NASTRAN analysis was to draw an enlarged half longitudinal cross section of the projectile. By modeling the section with single elements across the wall thickness, the computer run time was minimized. This resulted in a solution which gave the average stress across the thickness of the wall. It was theorized that some local yielding could be allowed as long as this did not result in yielding across the entire wall in any element. The average stress could therefore be used to design the projectile assuming the material was ductile enough to prevent cracking at points of a stress concentration.

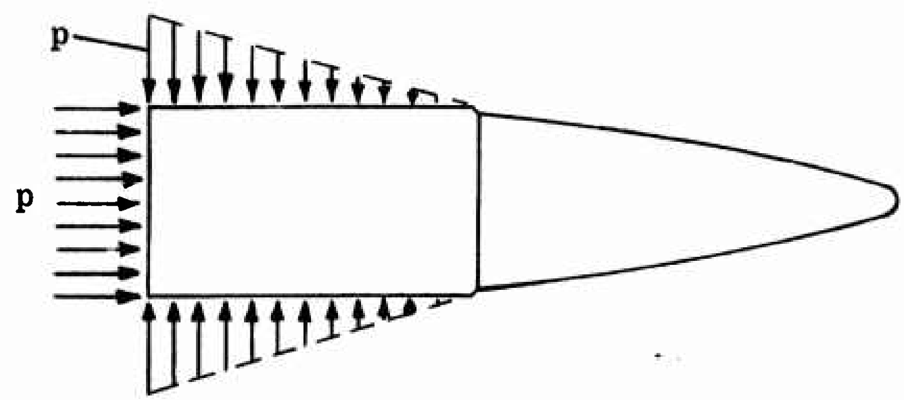
Applied loads were based on a peak base pressure of 51,726 psi. Three loads were considered as follows: a pressure load surrounding the base of the projectile, a torque load at the rifling band, and centrifugal loading due to projectile spin. The magnitude of each of these loads was determined from an interior ballistics analysis. The inertia relief format of NASTRAN can be used to give a pseudo-dynamic analysis by using dynamic loads to perform stepwise static analyses as the projectile traverses the barrel. The results of such an analysis very nearly approximate a dynamic analysis if the natural period is short compared to the period of the applied force, or restated, the stiffer the projectile, the better the approximation. Complete analyses at a series of positions along the barrel has consistently shown that peak stresses occur at peak pressure; therefore, for this projectile, analyses were performed at peak pressure and at the maximum spin rate, and again it was found that conditions at peak pressure governed the design.

A question arose concerning the probable distribution of pressure through the rotating band. Two types of loading distributions as shown in Figure 9 were investigated. The distribution shown in Figure 9a considered loading across the aft face only. The distribution shown in Figure 9b included a side load that varied linearly from the base value at the aft end to zero at the forward end of the rotating band. This latter distribution is considered the more conservative of the two. It resulted in lower stresses under the rotating band but higher stresses at the aft end. This distribution was used in the final stress computations.

The selection of a material and the heat-treat process was part of the structural design process. The use of a low carbon steel with a boron additive was contemplated, but this material, due to the small quantity required, could not be obtained in the required time at a reasonable price. The boron adds a through hardening property to low carbon steels. The low carbon steels are more ductile and easier to machine than the higher carbon varieties, and when boron is added these desirable properties are retained along with the added feature of through hardness. The second choice was a medium carbon steel. Successful experience had been realized with a 1040 steel in other designs so this material was chosen for this projectile. The material was heat treated to the R_C 38-42 range which gives a material tensile yield strength of 155,000 psi with adequate ductility. The allowable shear strength of this material is 89,900 psi. The design stress criteria chosen was the maximum shear theory of failure. The stresses that were computed were the octahedral shear stresses.



a. Aft Face Load Distribution Only



b. Aft Face and Side Load Distribution

Figure 9. Load Distributions on Rotating Band

The NASTRAN model used to compute the stress distributions in configuration 4I is shown in Figure 10. All dimensions used in the computation of stress were the minimum wall thicknesses shown on the drawings. The pressure used in these computations was the peak base pressure of 51,726 psi that occurs 3.10 seconds after ignition (see Table 1). Table 4 presents a listing of computed stresses. The elements shown in this listing can be located on the model.

Several elements under the rotating band show stresses that are in the region of the allowable stress; therefore, the design in this area represents a minimum weight configuration. Forward of the rotating band the stress levels are well below the allowable limit, and further thinning of the projectile wall from a structural viewpoint is a possibility. Other considerations, however, made this inadvisable. This 4I configuration shows a computed gyroscopic stability of 1.203 which is barely within the goal of 1.20 for this parameter. Thinning the wall in this forward region would have a detrimental effect on the CG location and the moments of inertia which would reduce stability below the desired minimum. Also, as indicated in a subsequent discussion, further thinning of the walls would have a detrimental effect on fragmentation properties, for a thin shell tends to produce fine fragments that are ineffective as a damage mechanism.

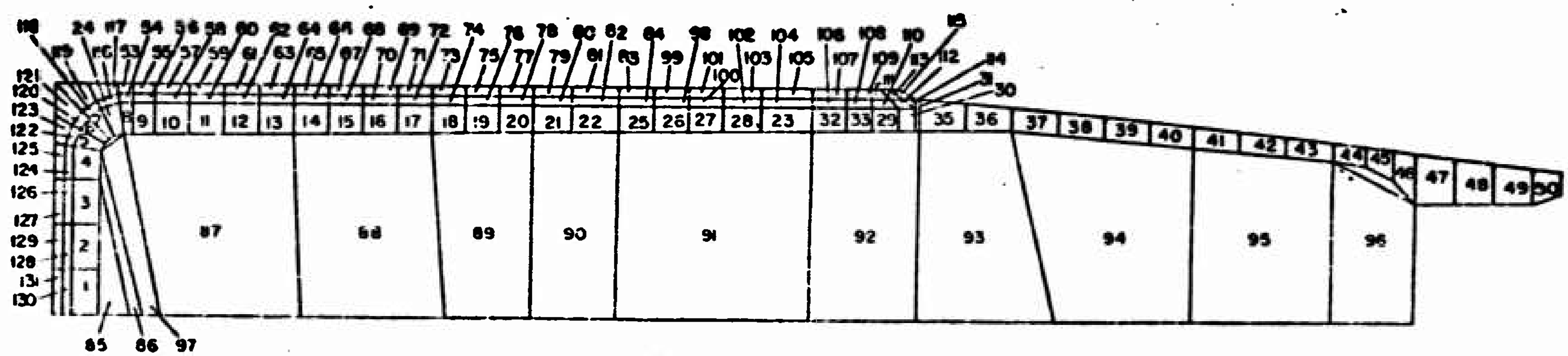


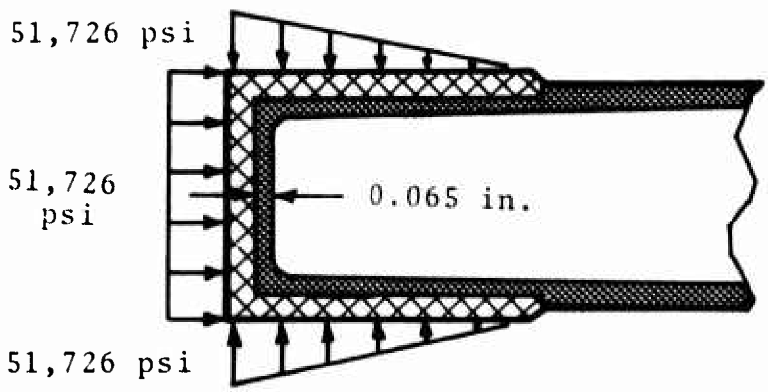
Figure 10. NASTRAN Model for Configuration 4I

TABLE 4. DISTRIBUTION OF STRESS - CONFIGURATION 4I

Element No.	Octahedral Stress (psi)	Element No.	Octahedral Stress (psi)	Element No.	Octahedral Stress (psi)
1	61162	43	62860	86	1643
2	75860	44	60276	87	137
3	89201	45	47888	88	333
4	74781	46	33477	89	519
5	41204	47	27889	90	597
6	33335	48	26762	91	687
7	38043	49	25908	92	733
8	52656	50	28326	93	743
9	75100	53	10516	94	711
10	74880	54	12998	95	668
11	77931	55	9672	96	633
12	82876	56	11167	97	570
13	86911	57	9421	98	2821
14	88442	58	10494	99	2569
15	89869	59	8815	100	2311
16	89508	60	9677	101	2093
17	87544	61	8251	102	1826
18	84054	62	8994	103	1628
19	81381	63	7740	104	1469
20	78084	64	8400	105	1298
21	73719	65	7247	106	1128
22	69932	66	7845	107	990
23	66427	67	6759	108	838
24	32914	68	7301	109	781
25	66608	69	6230	110	858
26	65309	70	6804	111	830
27	64480	71	5855	112	1253
28	64680	72	6318	113	949
29	67305	73	5408	114	2859
30	64772	74	5830	115	1586
31	45049	75	5449	116	1355
32	65366	76	5334	117	1045
33	66823	77	4483	118	1331
35	46695	78	4834	119	10249
36	53299	79	4050	120	13378
37	59428	80	4385	121	10424
38	60283	81	3680	122	13572
39	60549	82	4002	123	12331
40	61174	83	3126	124	13154
41	59614	84	3413	125	12331
42	61325	85	1458	126	13328

TABLE 4. DISTRIBUTION OF STRESS-CONFIGURATION 4I (CONCLUDED)

Element No.	Octahedral Stress (psi)
127	13,462
128	14,398
129	14,859
130	12,680
131	12,798



NOTES:

(1) Peak pressure 51,726 psi.

(2) Allowable octahedral stress 89,900 psi.

(3) Pressure applied at rear and side of projectile as shown in sketch.

4. INTERIOR BALLISTICS

The Air Force furnished information acquired in tests of GAU-7/A ammunition that provided the variation of chamber and base pressures with time and barrel travel (see Table 1). Reduction of the projectile weight, however, will affect these relationships. Both the theoretical and observed effect is that the peak pressures will be reduced, but the effect on muzzle velocity cannot be predicted without the benefit of extensive analysis or test because the burning properties of the propellant will be altered. The desired goal of increasing the muzzle velocity is achieved by tailoring the burning characteristics of the propellant to restore the pressure time and pressure travel relationship to the limits imposed by the gun. The Air Force indicated that this would be accomplished, and instructed that designs be developed to the GAU-7/A pressure information.

The variation of chamber pressure with time, specified in Table 1, was used to compute interior ballistic performance. The likely result is that the predicted muzzle velocities will be a little higher than will be realized in tests because barrel time will be reduced due to the higher velocities and pressure will not persist quite as long as indicated in the GAU-7/A information.

5. EXTERIOR BALLISTICS

Exterior ballistic considerations of interest in designing the projectile were projectile stability and the variation of the downrange velocity.

Three stability parameters were computed for the projectile. These parameters were gyroscopic stability (S_g), dynamic stability (S_d), and a relationship between these two parameters.

Stability parameters were computed under conditions of forward fire from a 715 KTAS aircraft at sea level, and a -40°F temperature. Stability requirements are mathematically defined by the following criteria:

$$S_g \geq 1$$

$$0 < S_d < 2$$

$$S_g \geq 1/S_d(2 - S_d)$$

Gyroscopic stability was the only parameter that required monitoring in this projectile. Although mathematically a stable condition exists if $S_g \geq 1$, a practical value for this parameter is 1.20, and designs were developed to satisfy this criterion. This had a practical implication in designing the 4I configuration, for the walls forward of the rotating band could have been thinned further by structural standards, but this would have resulted in a stability deficiency.

Gyroscopic and dynamic stability are defined by the following expressions:

$$S_g = \frac{8 \pi A^2}{\rho n^2 d^5 B C_{m\alpha}} \left(\frac{V}{U}\right)^2$$

$$S_d = \frac{C_{N\alpha} - C_{Do} + \left(\frac{k_1}{2}^{-2}\right) C_{np\alpha}}{C_{N\alpha} - C_{Do} - \left(\frac{k_2}{2}^{-2}\right)(C_{mq} + C_{m\dot{\alpha}}) + \left(\frac{k_1}{2}^{-2}\right) C_{\ell p}}$$

where:

d = projectile diameter - ft

A = axial moment of inertia - slug-ft^2

B = transverse moment of inertia - slug-ft^2

n = twist rate of barrel - cal/turn

ρ = air density - slug/ft^3

V = projectile muzzle velocity - ft/sec^2

U = projectile velocity with respect to air - ft/sec^2

$C_{N\alpha}$ = normal force coefficient derivative

$C_{m\alpha}$ = pitching moment coefficient derivative

C_{Do} = zero yaw drag coefficient

$C_{np\alpha}$ = magnus moment coefficient derivative

$C_{mq}+C_{m\dot{\alpha}}$ = damping in pitch coefficient derivative

$C_{\ell p}$ = spin deceleration coefficient

m = mass - slug-ft^2

$$k_1 = \frac{A}{md^2}$$

$$k_2 = \frac{B}{md^2}$$

Further, it is noted that

$$C_{m\alpha} = C_{N\alpha}(x_{cg}-x_{cp})$$

where: x_{cg} = projectile center of gravity measured from nose

x_{cp} = projectile center of pressure measured from nose.

Using the following input data for the 4I configuration, the stability factors shown in Figure 11 were computed for varying values of the total projectile velocity (U).

d = 0.082 ft

A = 0.03976 lb-in^2

B = 0.496759 lb-in^2

n = 22.87 cal/turn

ρ = 0.003278 slugs/ft^3

$C_{N\alpha}$ = 2.507

$C_{mq} + C_{m\dot{\alpha}}$ = -21.444

C_{Do} = 0.165

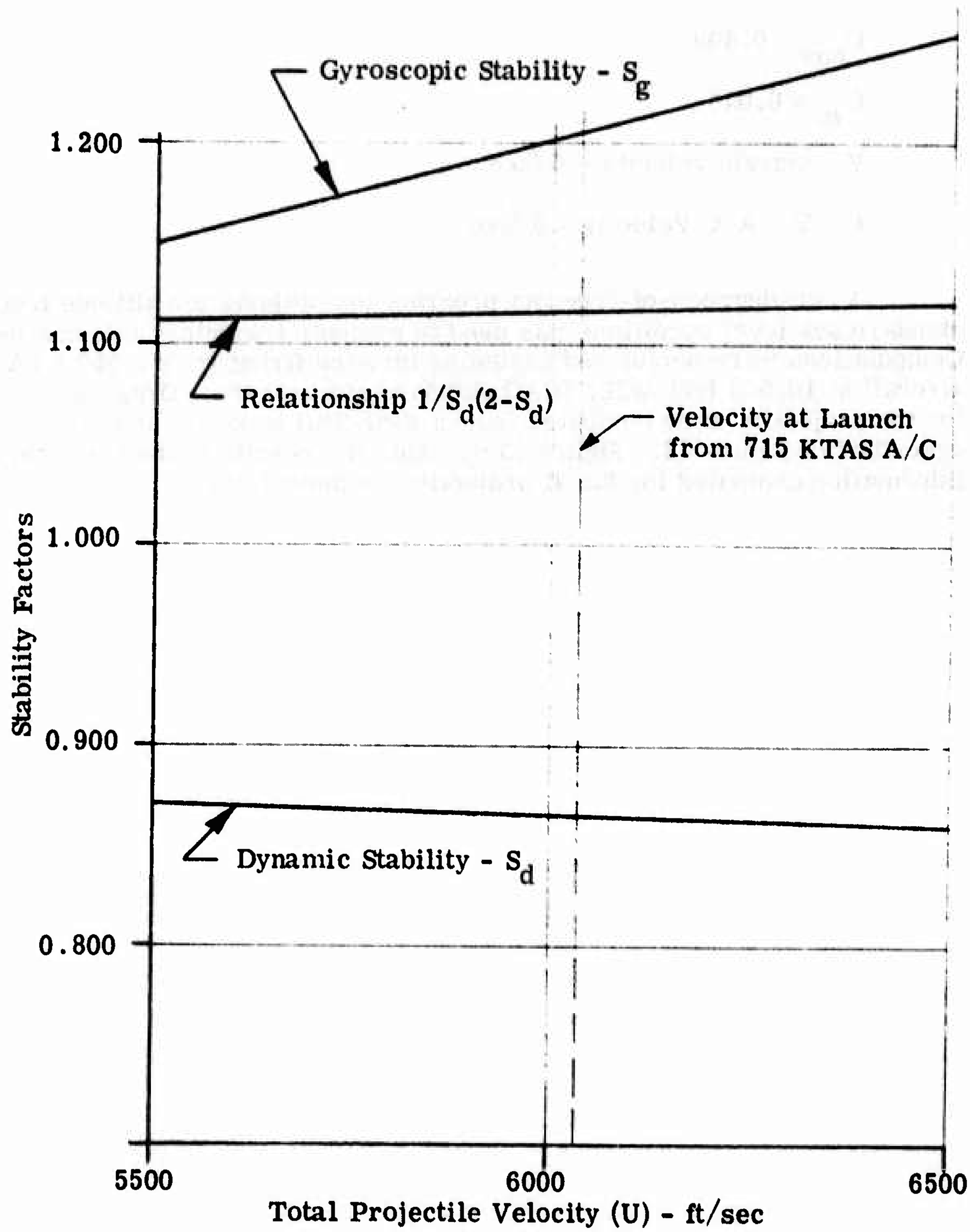


Figure 11. Stability Factors - 41 Projectile Configuration

$C_{np\alpha} = 0.409$

$C_{\ell p} = 0.014$

V = muzzle velocity - ft/sec

U = V + A/C Velocity - ft/sec

A two-degrees-of-freedom program that adjusts for altitude from standard sea level conditions was used to compute trajectory information. Computations were performed assuming forward firing from a 550 KTAS aircraft at 10,000 feet MSL, ICAO standard atmosphere. Drag coefficients for the projectile were computed from a SPINNER program and are described in Figure 12. Figure 13 presents the results of the trajectory information computed for the 4I projectile configuration.

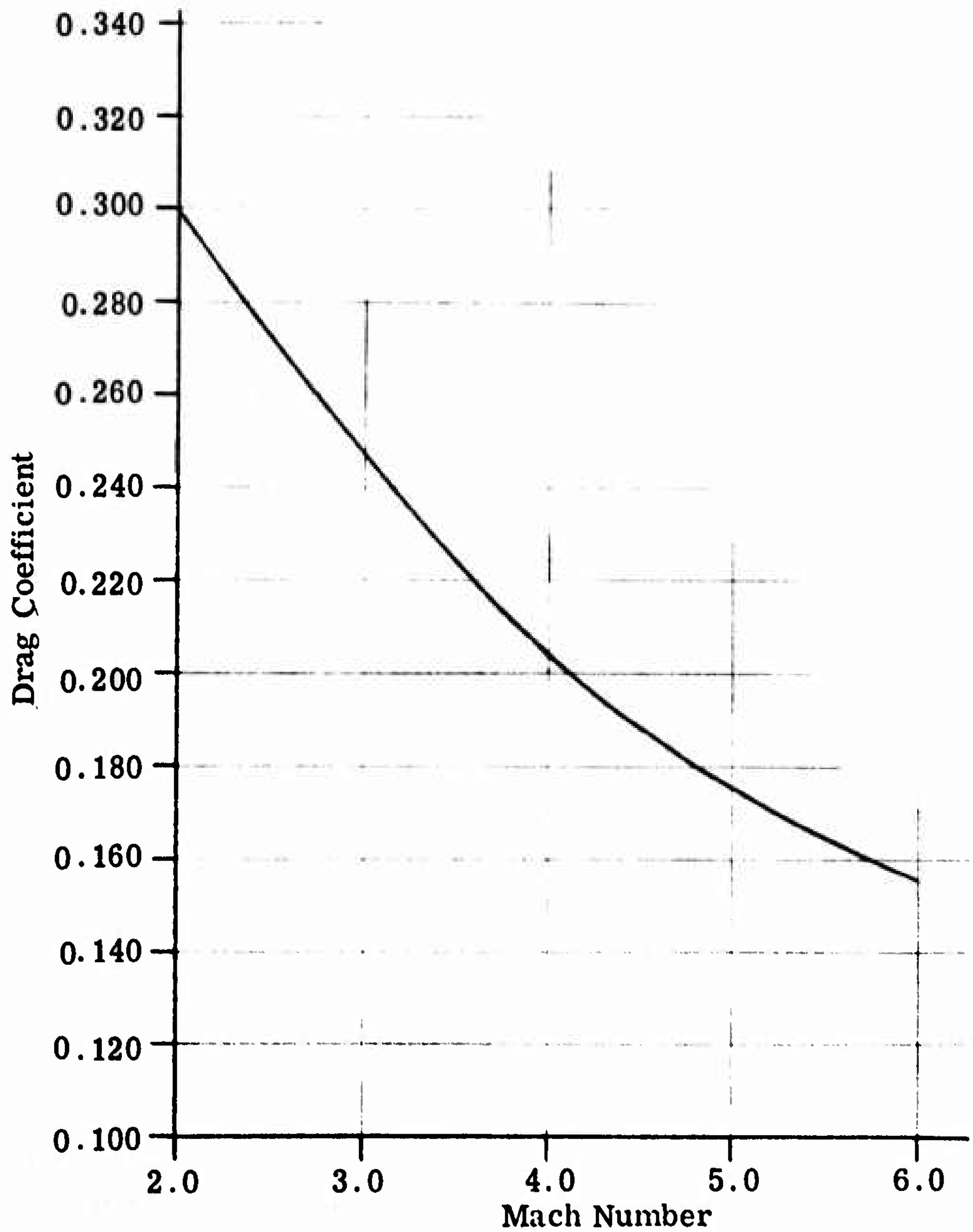


Figure 12. Drag Coefficients for 4I Projectile Configuration

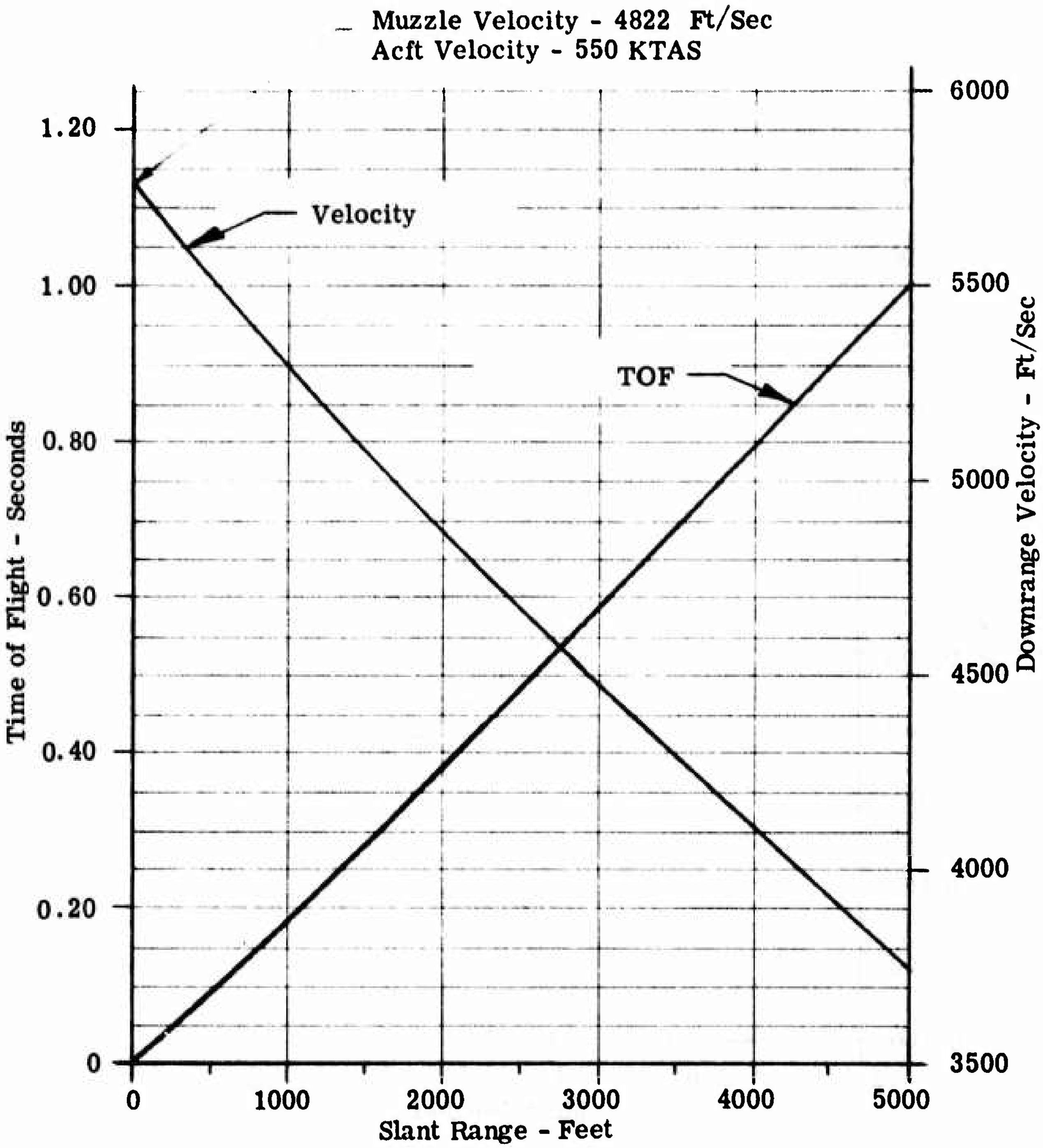


Figure 13. Trajectory Information - 4I Projectile Configuration

6. TERMINAL BALLISTICS

The primary damage mechanisms of the projectile against enemy aircraft are blast, high velocity fragments and fire. Blast inflicts structural damage, whereas fragments penetrate critical target components, releasing fuel and other volatile substances and inflict general physical damage. Pyrophoric elements in the HE and projectile ignite the combustible materials released by the blast and fragments. No attempt was made to treat analytically blast and pyrophoric effects. Fragmentation properties were investigated using empirical relationships developed by GURNEY to predict flyoff velocities and MOTT to project fragment distributions.

The charge-to-mass ratio appears in the Gurney expression for flyoff velocity, and a large charge-to-mass ratio is usually indicative of good projectile design. These lightweight projectiles are excellent designs in this respect, having a charge-to-mass ratio in the region of 0.60 compared to 0.25 for the GAU-7/A, PJU-2/B HEI projectile.

Flyoff velocities were computed according to the following empirical relationship developed by Gurney:

$$V_f = \sqrt{2E}\sqrt{\frac{C/M}{1 + \frac{C}{M}\left[\frac{3 + a_r}{6(1-a_r)}\right]}}$$

where: V_f = flyoff velocity - ft/sec

$\sqrt{2E}$ = constant depending upon the explosive - 8800

C = charge weight

M = weight of projectile shell

a_r = ratio of explosive core radius to inner shell radius = 1.0

The velocity computed from this relationship was added vectorily to the projectile velocity (U) at 2500 -foot range to obtain the total flyoff velocity. For the 4I projectile configuration the following result is obtained:

$$V_f = 8800 \sqrt{\frac{\frac{626}{1082}}{1 + \frac{626}{1082}\left[\frac{3+1}{6(1+1)}\right]}}$$

$$= 6129 \text{ ft/sec}$$

$$V_{tot} = \sqrt{V_f^2 + U^2}$$

$$= \sqrt{6129^2 + 4658^2}$$

$$= 7698 \text{ ft/sec}$$

The following empirical expression developed by MOTT was used to investigate fragment distribution:

$$N(w) = \frac{W}{2\mu} e^{-\left(\frac{w}{\mu}\right)^{\frac{1}{2}}}$$

where: $N(w)$ = number of fragments greater than weight, w.

W = weight of entire fragmenting shell - grams

μ = fragment mass constant - grams

w = weight of fragment - grams

and: $$\mu = \left[B t_o^{5/6} d_i^{1/3} \left(1 + \frac{t_o}{d_i}\right)\right]^2$$

where: t_o = casing thickness - inches

d_i = internal shell diameter - inches

B = constant = 1.13

Fragment distributions were computed for the different projectiles using an average wall thickness. For the 4I configuration $t_o \approx 0.063$ inches, $d_i \approx 0.802$ inches, and W = 70.11 grams (1082 grains). Using this information and the Motts expression, the fragment distribution shown in Table 5 is obtained. This computation indicates that 19 percent of the fragments can be expected to be in the weight range from 5 to 15 grains. The Air Force

has indicated that a goal of 25 to 30 percent in this weight range is desirable. An increase in the wall thickness to 0.070 to 0.075 inch would, according to predictions based on Motts, achieve this goal. This, however, would require departure from a minimum weight design so a trade-off situation arises. Tests planned for the projectile should provide information that will aid in reaching trade-off decisions.

TABLE 5. FRAGMENT SIZE DISTRIBUTION - CONFIGURATION 41

W (grains)	W (grams)	N(w)	No. of Frags of Size w	Wt of Frags (grains)	Percent of Total Wt
≤1	0.0648	288		244	23
2	0.1296	114	174	348	32
3	0.1944	56	58	174	16
4	0.2592	30	26	104	10
5	0.3240	18	12	72	7
6	0.3888	11	7	42	4
7	0.4536	7	4	28	3
8	0.5184	5	2	16	1
9	0.5832	3	2	18	1
10	0.6480	2	1	10	1
11	0.7128	2	0	0	0
12	0.7776	1	1	12	1
13	0.8424	1	0	0	0
14	0.9072	0	1	14	1
15	0.9720	0	0	0	

7. FABRICATION

The metal part of the projectile in this program was machined from bar stock. In quantity production a cup and draw process might be considered but this could not be considered on this exploratory development program due to the expense of the tooling.

The machining procedure was to machine the internal portions of the projectile to final configuration before heat treat. The outside diameter was left about 0.040 inch oversize for finishing after heat treatment. The projectile was heat treated and then machined to its final configuration. A fast oil quench was specified for the heat treat process to minimize distortion.

This fabrication process gave very satisfactory results. The removal of chips through the 0.563 inch diameter opening at the fuze end of the projectile when machining the interior surfaces presents a problem and slows down the machining process. This, however, is inherent to the machining method of manufacture and cannot be avoided. The problem responded to some techniques developed by the machinist and diminished in severity as experience was acquired.

Application of the rotating band encountered problems that were resolved by experimentation and experience. One of the problem areas was preventing the adhesive film that is applied to the projectile prior to injection molding from washing away when the hot plastic is injected into the mold. This was resolved by wrapping the adhesive tightly around the projectile and securing the wrap with heat applied with a soldering iron. Another problem was accomplishing a satisfactory cure. A satisfactory plastic-to-metal bond cannot be achieved unless the adhesive is cured properly. It was found that positive pressure must be maintained at the plastic projectile interface during the curing process, and the cure time must be sufficient to create the bond. These problems were resolved by pressing a sleeve onto the projectile to create pressure along the sides. Pressure at the aft end was achieved by fitting a plate to the plastic and clamping the projectile from its base to its mouth during cure. A curing time of 1.50 hours at 325-340°F was necessary to accomplish the bond.

The complete process used to prepare the projectile and apply the rotating band is as follows:

Projectile Surface Preparation

(1) Vapor degrease in perchloroethylene.

(2) Grit blast the recessed band seat with clean dry alumina and clean dry air.

(3) Vapor degrease in perchloroethylene.

(4) Ultrasonic clean in prebond 700 caustic solution (283 grams/ gallon of water) for a minimum of 5 minutes at 200 $\pm 10^{o}$F.

(5) Rinse in deionized water with ultrasonic agitation for a minimum of 5 minutes at 190 $\pm 10^{o}$F.

(6) Rinse in acetone.

(7) Apply a uniform coating of M&T chemicals 253-P Nylon primer to projectile recessed band seat area.

NOTE: Paragraphs (3) through (7) should be conducted in a continuous operation. The projectile should not be allowed to dry between any step of the processing.

(8) Air dry for 30 minutes at room temperature.

(9) Cure the primed projectiles at 250^{o}F for 75 minutes. Cool to room temperature and store in a noncontaminated atmosphere.

Adhesive Application

(1) Apply one ply of American Cyanamide FM1000 film adhesive to the recessed area band seat. The film thickness is 0.003 inch and weighs 0.015 lb/ft^2. The adhesive may be butt-overlapped a maximum of 0.060 inch. Heat tack the overlapped film area together.

(2) Store the adhesive-covered projectile in a contamination-free package below 80^{o}F until injection molded. Injection molding must occur within 3 days after adhesive application.

Injection Molding

(1) Vacuum dry Zytel 158 nonlubricated nylon to less than a 1 percent moisture content.

(2) Position the adhesive-coated projectile in a 120 $\pm 10^{\circ}$F mold and injection mold using processing conditions which are applicable to the particular injection molding machine and the Zytel 158.

(3) Remove projectile from mold and cool to room temperature. Place the projectile in the steel retaining ring and clamp the projectile between its base and mouth to prevent the projectile from moving away from the nylon. Cure in a nitrogen purged vacuum oven that is at 15 to 10 inches of Hg for 90 minutes at 325°F to 345°F.

(4) Cool to room temperature, remove retaining ring and final machine the plastic band to the required dimensions.

SECTION III

PRELIMINARY FUNCTIONAL CONFIGURATION IDENTIFICATION

The following information has been prepared to identify the functional characteristics of this 25mm lightweight projectile.

1. PHYSICAL CHARACTERISTICS

The principal physical characteristics of the four projectile configurations that were designed and analyzed on this program are listed in Table 6. Configuration 4I was selected for fabrication and both predicted and actual information on this configuration are provided. The information on the other configurations was computed only. The 4I configured projectile was fabricated of 1040 steel heat treated and drawn to R_C 38-42 hardness. The plastic rotating band was molded in place and is bonded to the surface of the projectile.

2. PERFORMANCE CHARACTERISTICS

Performance characteristics are separable into three categories: interior ballistics, exterior ballistics, and terminal effects. This program provided for analysis and design only, so performance parameters are predicted values derived by analytical means. Table 7 contains a listing of the performance parameters computed for the final version of each of four projectile configurations.

3. RELIABILITY

Reliability goals for projectile functioning were not specified. The fuzing and HE system used in this projectile are identical to the GAU-7/A system and reliability commensurate with that projectile can be expected.

4. MATERIALS

The materials used in this projectile are standard and readily available. The projectile body was fabricated of 1040 steel. This material was heat treated to R_C 38-42 using a fast oil quench. The rotating band material is nylon 612, Zytel® 158 grade. The materials used to bond the rotating band to the projectile body are standard and commercially available. The HE explosive is the Lake City formula used in 20mm ammunition and is available from the Lake City Arsenal.

TABLE 6. PHYSICAL PROPERTIES OF FOUR LIGHTWEIGHT PROJECTILE CONFIGURATIONS

Configuration	Drawing	Weight (grains)					Inertia ($\#\text{-in}^2$)		CG (1) Inches
		Case	Rotating Band	Fuze	HE	Total	Polar	Tranv	
Conf 4I									
Computed	Figure 6	1082	114	508	626	2330	0.039760	0.496759	1.85
Actual	Figure 7	1145	85	517	622	2369	-- (2)	-- (2)	1.91
Conf 3C	Figure 5	1290	70	508	553	2421	0.038426	0.449465	1.96
Conf 2B	Figure 4	1156	44	508	654	2361	0.041339	0.510852	1.83
Conf 1A	Figure 3	1125	44	508	661	2338	0.040963	0.503516	1.85

(1) Measured from the base of the projectile.
(2) No measurement taken.

TABLE 7. PERFORMANCE PARAMETERS OF FOUR LIGHTWEIGHT PROJECTILE CONFIGURATIONS

Configuration	V Muzzle (fps)	Stability			TOF(1) (Sec)	Terminal		
		Gyroscopic S_g	Dynamic S_d	$\frac{1}{S_d(2-S_d)}$		C/M	Flyoff Vel (fps)	Frags (2) (percent)
Conf 1A	4785	1.24	0.86	1.02	0.45	0.59	7783	
Conf 2B	4756	1.21	0.87	1.02	0.48	0.57	7477	
Conf 3C	4663	1.17	0.85	1.02	0.43	0.43	6983	24
Conf 4I	4827	1.20	0.87	1.02	0.49	0.60	7598	19

(1) Time of Flight to 2500 feet.

(2) Percent of fragments between 5 and 15 grains.

5. INTERFACE CHARACTERISTICS

Two interface requirements were applicable to the design of this projectile. One required that the projectile be designed for launch from a GAU-7/A gun barrel. This influenced the dimensions of the exterior of the projectile and the design of the rotating band. The other interface is with the cartridge case. The crimp groove in the rotating band was designed to satisfy this interface consideration.

6. TEST REQUIREMENTS

Contractor responsibilities on this program were for analysis and design only, and no performance testing was conducted. Table 8, however, presents a list of tests recommended to check the performance of this projectile.

TABLE 8. SUMMARY OF RECOMMENDED TESTING

Characteristics	Nature of Test	Test Responsibility
Projectile Hardness	a. Uniform hardness - Rockwell penetrator b. Through hardness - Macro-Etching	Contractor
Structural Integrity	Photograph projectile at muzzle exit by X-ray and microflash and inspect for structural deformation.	Government or contractor
Plastic-to-Metal Bond Rotating Band	Microflash photographs of projectile in flight.	Government or contractor
Chamber Pressure	Time-pressure variation of chamber pressure measured by transducer and recorded on Polaroid film.	Government or contractor
Muzzle Velocity	Time to traverse a known distance obtained by chronograph measuring.	Government or contractor
Dispersion	Impact pattern recorded on witness sheet placed at known target distance.	Government or contractor
Stability	Damping of flight perturbations recorded photographically at known intervals.	Government
Drag	Velocity decay rate - multiple chronograph measurements or radar tracking.	Government

TABLE 8. SUMMARY OF RECOMMENDED TESTING (CONCLUDED)

Characteristic	Nature of Test	Test Responsibility
Penetration Capability	Impact target and photograph projectile with X-ray or microflash	Government or contractor
Fragment Velocity	Explode projectile in arena and photograph particles at known times	Government or contractor
Fragment Distribution	Recover fragments in arena, sort by size, and count to obtain distribution	Government or contractor
Spatial Distribution	Recover in gel or photograph by X-ray	Government or contractor
Incendiary Properties	Fire into prepared targets and determine fire ignition capability	Government

SECTION IV

CONCLUSIONS

The following conclusions are drawn from the experience and findings of this program:

- o The designs presented herein represent the minimum weight that can be achieved without the sacrifice of projectile stability margins and the reduction of fragmentation properties below desired goals.

- o The stress levels employed in these designs are at or near optimum for this lightweight projectile, for they lead to a projectile shell design where structural properties and stability and fragmentation considerations are satisfactorily balanced.

- o A1S1 1040 steel and the heat treat process employed in this projectile are an adequate combination for the design of this lightweight projectile. This combination may be only one of several practical solutions, but it provides the direction and a precedent in the search for a suitable material and heat treat process for this lightweight projectile.

SECTION V

RECOMMENDATIONS

The margins on structural integrity and projectile stability have been reduced to their theoretical minimum in developing this projectile design. Also, the computed fragmentation distributions show marginal acceptability. These values have been developed analytically, but will be investigated experimentally by the Air Force. Refinement of the designs to correct the deficiencies, if any, is a practical proposition; therefore, the following approach to the further development of this projectile is suggested:

- Conduct sufficient tests to observe and/or measure the structural integrity, projectile stability, and the fragmentation properties of the present design. Base corrective measures, if required, upon the results of these tests.

- Observe the performance of the rotating band under varying environmental conditions, and plan any further development effort on the results of these tests. Materials, the configuration of the band, and the application process are areas for modification in achieving a reliable rotating band.

- The choice of a material and refinement of the heat treat process are areas that should receive continued attention. The material should heat treat properly, satisfy structural requirements, and be the most economical from standpoints of its raw material cost and its workability.

- Continued investigation of terminal effects is suggested. The size and spatial distribution of the fragments are needed to determine the influence, if any, on the configuration of the projectile walls.

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INITIAL DISTRIBUTION

HQ USAF/RDQRM	1	AFATL/DLDL	1
HQ USAF/SAMI	1	AFIS/INTA	1
HQ USAF/XOXFCM	1	ARADCOM/SARPA	1
AFSC/IGFG	1	NAV ORD LAB	1
AFIT/LD	1	OGDEN ALC	2
ASD/ENFEA	1	ASD/ENESS	1
TAC/DRA	1	AFATL/DLA	1
SAC/LGWC	1	ADTC/SDC	1
WRAMA/MMEBL	1	NAV SURF WPNS CTR	1
AFWL/LR	1	FRANKFORD ARSENAL	1
AUL/LSE 71-249	1		
REDSTONE SCI INFO CTR	2		
USA WPNS CMD/SAPTR-LW-A	1		
USA MAT SYS ANA AGN	1		
SARPA-PAC-TILO/QRI	1		
SARPA-TS	1		
NAV SURF WPNS CTR	2		
NAV ORD STN	1		
NAV WPNS STN/20323	1		
USN WEA CTR/CODE 233	2		
NAV AIR SYS CMD/AIR-5323	1		
IRIA CTR	1		
DDC/TC	2		
USAFTFWC/TA	1		
SARWV-RDT-L	1		
PLASTEC-BLDG 3401	1		
NAV WPN CTR/CODE 3123	1		
OO-ALC/MMWMP	2		
AF SPEC COM CTR/SUR	3		
HQ DEPT OF ARMY/DAMA-WSA	2		
SARPA-FR-S-A	1		
AEDC/AEO, INC	1		
USA MAT SYS ANA AG/AMXSY-DS	1		
NAV OPNS 76/OP-982E)	1		
USAFTAWC/TX	1		
AFATL/DL	1		
AFATL/DLY	1		
AFATL/DLOU	1		
USAFE/DOQ	1		
PACAF/DOOFQ	3		
AFATL/DLODR	1		
COMIPAC/I-232	1		
ASD/XRP	1		
USA TRADOC SYS ANA ACT	1		
TAC/INA	1		
AFATL/DLODL	9		
AFATL/DLYV	1		

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